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FRAGILITY ANALYSIS OF EXISTING STEEL BUILDING AND POSSIBLE REHABILITATION BY FUZZY EXPERT SYSTEMS UNDER BLAST AND DYNAMIC LOADS

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ABSTRACT

During recent years fragility analysis (FA) of steel building frame is investigated which can be used for preliminary estimate of its probability of failure. The risk analysis in FA procedure uses the format of probabilistic Risk Analysis and considers band limited white dynamic velocity at the bed rock as the seismic input and structural reflect. In this research as a case study, 67 steel building frame is modelled and analysied by pushover analysis with response of the steel frame is obtained by response spectrum method of analysis for multi-degree of freedom system. This paper focused on an analytical method for constructing fragility curves of a given class of existing structures, based on a stochastic approach and fuzzy expert system algorithm. In stochastic analysis the problem is related to the well-known threshold crossings theory connected to the evaluation of structural reliability. In many structural problems the most used reliability definition is the probability that system will not have a failure associated to a bilateral threshold crossing of a given level in the time interval. Fragility fuzzy curves are obtained in terms of probability of exceeding a given damage level by us- ing an approximate crossings theory of stochastic processes and compare with most used probabilistic approach that system will not have a failure associated to a bilateral threshold crossing of a given level in the time interval.

KEYWORDS: Fragility Analysis, Steel Frame, Fragility curves, Fuzzy Expert Systems

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Original Article

INTRODUCTION

During recent deaced, China sub-continent has history of devastating earthquakes. The major reasons for high frequency of earthquakes are that china is driving into Asia at the rate of 53mm/year. Geographical statistics of China showed that 34% of the land is vulnerable to earthquakes. The recent devastating earthquakes have exposed the vulnerability of existing steel frame and steel buildings in China.

So by this resone, need for evaluating seismic adequacy of the existing structures has come into focus following the damage and collapse of numerous concrete structures. Vulnerability assessment of both old and new structures forms the critical components of the pre-disaster mitigation strategy in which retrofitting is an integral part. A timely assessment is necessary to establish the need for strengthening and retrofitting of the structure to enhance their strength to withstand major hazards. Seismic vulnerability of structures in regions of high seismicity therefore requires considerable attention in recent years. Seismic risk analysis of all important and specialty structures like hospitals, nuclear power plants, long span bridges, dams, lifeline structures etc., are now invariably

carried out in zones of high seismicity[8,26].

PROCESS OF MODELLING IN ABAQUS FEA

One of most general software which work on finite element package is ABAQUS FEA. So by this inoduction a structural model has been created to undertake the non linear analysis. Beams and columns are modeled as nonlinear frame elements with lumped plasticity at the start and the end of each element[25]. ABAQUS FEA provides default-hinge properties and recommends PMM hinges for columns and M3 hinges for beams as described in ASCE-FEMA-356 and GB 500011-2001.

Structural Dynamic Model Input

By this regard, seismic input consists of band-limited white noise power spectral density function (PSDF) at the bedrock level. From PSDF of white noise at the bed rock, response spectrum at free field is generated by the seismic wave propagation analysis in frequency domain through the overlying layer of soil[16]. The response spectrum corresponding to the free field ground motion is taken as the input to the structure.

Frequency Spectral Analysis

The power spectral density function (PSDF) of the absolute acceleration of the free field ground motion is related to the PSDF of the ground acceleration of the bedrock by the following relationship:

$$S_f(\omega) = A(\omega)^2 \times S_0$$

Where, $S_f(\omega)$ is the PSDF of the absolute acceleration of the free field ground motion; $A(\omega)$ is the transfer function for the free field absolute acceleration; S_0 is the constant PSDF of the white noise at bedrock[9]. For uniform linear soil, $A(\omega)$ can be obtained by solving the one dimensional wave equation through soil medium as given by Kramer[16]. $A(\omega)$ is defined by:

$$A(\omega) = \frac{u_0(t)_{\max}}{u_H(t)_{\max}}$$

Note that u denotes absolute acceleration. The transfer function in the closed form for uniform soil layer of thickness H; shear wave velocity V_s and percentage critical damping of soil ξ is given by:

$$A(\omega) = \frac{1}{\sqrt{\cos^2(\frac{\omega H}{V_s}) + \left(\frac{\xi \omega H}{V_s}\right)^2}}$$

H is thickness for uniform soil layer; Vs is shear wave velocity and ξ is percentage critical damping of soil. At the bedrock level only PGA is known. Since band limited white noise acceleration is assumed at the bedrock level for the ground acceleration, S_0 can be related to the PGA in the following manner.

$$S_0 = \frac{(PGA)^2}{p_f^2 \times \omega_c}$$

Where ω_c is cutoff frequency in rad/sec. Pf is the peak factor, which is obtained from the three moments of the PSDF of the absolute acceleration of the free field ground motion given by Vanmarcke [28]. Where ωc is cutoff frequency in rad/sec. Pf is the peak factor, which is obtained from the three moments of the PSDF of the absolute acceleration of the free field ground motion given by Vanmarcke [28].

RESPONE SPECTRUM OF FRAME

So, the PSDF of free field absolute acceleration is obtained, the corresponding response spectrum may be derived by using inverse of the relationship given by Der Kiureghian [9] as written below:

$$S_f(\omega) = \frac{\omega^{\theta+2}}{\omega^{\theta} + \omega_{ff}{}^{\theta}} \times \left[\frac{2\xi\omega}{\pi} + \frac{4}{\pi\tau}\right]\left[\frac{D_j(\omega_i \xi)}{P_f}\right]^2$$

Where, ω is frequency in radians per seconds, τ is the duration of earthquake shaking and taken as 15 sec; ωff and θ are two constants which can be obtained by iteration procedure; however values of ωff and θ taken as 0.705 and 3.0; $D_j(\omega_i \xi)$ is the ordinate of the risk consistent response spectrum for displacement.

Determination of Faragility Curve

The response (that is, the moment) R for the section is random variable given by:

$$R = M \times F_1 \times F_2 \times F_3 \times F_4$$

in which M is computed moment at the critical section (shown in figure 3); F1, F2, F3, and F4 are uncertainty factors considered due to variation in earthquake loading, structural and soil properties, modelling of structure and type of analysis considered.[4] Similarly, the capacity for the section is a random variable, which is a product of three variables, namely:

$$C = M_p \times F_5 \times F_6$$

in which, Mp is the plastic moment capacity of the section calculated based on the material property with a coefficient of variation as β5 and β6; F5 and F6 are uncertainty factors considered due to variation in ductility and damage concentration effect. Using First Order Second Moment (FOSM), the probability of failure Pf for the section is given by Ranganathan [25]:

$$P_f = P\left[(C - R) \le 0\right] = 1 - \varphi(\beta)$$

Where β is:

$$\beta = \frac{\ln\left(\frac{C}{R}\right)}{\sqrt{\sigma^2_{In(R)} + \sigma^2_{In(C)}}}$$

Where R and C are the median values and $\sigma_{In(R)}$ and $\sigma_{In(C)}$ are the logarithmic standard deviations of the resistance and capacity of the structure respectively[22]. Thus, the denominator of the equation can be replaced by:

$$\left(\sigma^2_{In(R)} + \sigma^2_{In(R)}\right) \times \left(\frac{1}{2}\right) = \sqrt{\beta^2_1 + \beta^2_2 + \beta^2_3 + \beta^2_4 + \beta^2_5 + \beta^2_6}$$

where β is the coefficient of variation of different uncertainty factors. Fragility curve is the plot of probability of failure with PGA.

EARTHQUAKE RECORDS SELECTIONS

As mentioned earlier, 10 earthquake records of Iran and the other sites of the world are used in this paper. The near fault effect is also considered in choosing some of these records. The records used in this research an: shown in Table 1, with their corresponding seismic parameters.

Table 1: Earthquake Records

Earthquake	**Cape Mendocino**	**Kobe**	**Chi Chi**	**Morgan Hill**	**Loma Prieta**	**Northridge**	**Kobe**	**Elcentro**	**Manjil**	**Tabas**
Date	1992/04/25	1995/01/16	1999/09/20	1984/04/24	1989/10/18	1994/01/17	1995/01/16	2001	1990	1978/09/16
Station	89005 Cape Mendocino	Takatori	CHY006	Gilroy Array #1	Gilroy Array #1	Tarzana, Cedar Hill	KJMA	ElCentro Array #11	Qazvin	9101 Tabas
PGA(g)	0.754	0.24	0.364	0.092	0.209	1.048	0.343	0.053	0.0883	0.852
Soil Type (Geomatrix)	Rock	Soft (deep) soil	Deep (broad) soil	Rock	Rock	Shallow (stiff) soil	Shallow (stiff) soil	Deep (broad) soil	Deep (broad) soil	Deep (narrow) soil

FRAGILITY ANALYSIS DAMAGE INDIXES

When buildings are subjected to earthquakes, various states of damage occur. The maximum deformation, the hysteric behaviour and the deformation and energy absorption are structural re- sponse parameters used to define these three types of damage indices[1]. Deformation based non- cumulative damage indices as the drift ratio and the displacement ductility, have the advantage of simplicity in calculations. Also, the drift values are typical values provided to illustrate the overall structural response associated with various structural performance levels[3]. So, in this study a deformation based damage index, that is the interstorey drift, will be used and three damage states are considered:

- Immediate Occupancy
- Life Safety
- Collapse Prevention

These damage states are defined, using the structural performance levels and damage pro- posed by FEMA356[12]. The values of drift of structural performance levels are presented in table 2. The nonlinear analysis

program, IDARC and ANSYS, is used to model the buildings and calculate the damage indices. In this program drift ratio, story drift, displacement, velocity and storey veloc- ity drift can be calculated for each storey as the maximum response by using weight coefficient on the basis of hysteretic energy was dissipated in elements[27,14]. Based on maximum drift ratio of each frame, storey drift and storey velocity drift have been used in stochastic process and obtaining the fragility curves[15].

Table 2: Structural Performance Levels and Damage

Elements	Type	Collapse Prevention S- 5	Life Safety S-3	Immediate Occupancy S-1
Steel Frames	Primary	Extensive cracking and hinge formation in ductile elements. Limited cracking and/or splice failure in some nonductile columns. Severe damage in short columns.	Extensive damage to beams. Spalling of cover and shear cracking (<1/8" width) for ductile columns. Minor spalling in nonductile columns. Joint cracks <1/8" wide.	Minor hairline cracking. Limited yielding possible at a few locations. No crushing (strains below 0.003).
	Secondary	Extensive spalling in columns (limited shortening) and beams. Severe joint damage. Some reinforcing buckled.	Extensive cracking and hinge formation in ductile elements. Limited cracking and/or splice failure in some nonductile columns. Severe damage in short columns.	Minor spalling in a few places in ductile columns and beams. Flexural cracking in beams and columns. Shear cracking in joints <1/16" width.
	Drift	4% transient or permanent	2% transient; 1% permanent	1% transient; negligible permanent

NUMERICAL MODELLING OF BUILDINGS

Define Strcutures

Since buildings as the main part of a city are about 80 percent of vulnerable structures, their damage during an earthquake should be assessed[2,6]. After separating to two regions on the basis of soil type, the most widely used structural system was selected and nonlinear dynamic analysis with IDARC and ANSYS will be done by considering interaction of soil-structure that was men- tioned in the last part. Studying on about 150 structures with frame system has been done and the frames separately are shown in table 3.

According to the Table 3 Moment Steel frame-shear wall for region 1 with 32.84% and Moment Steel frame for region 2 with 35.71% were selected for modelling. Number of stories for analysis should be included a lot of buildings. Based on the observa- tions in Tabriz and after structural system selection, the frames were chosen with 4, 8 and 12 stories and 4 spans for analysis. The other properties of frames are shown in table 4.

Table 3: Steel Frames Numbers

Frame	Region 1		Region 2	
	Number of Frames	Percentage (%)	Number of Frames	Percentage (%)
Moment Steel frame	18	26.87	30	35.71
Moment Steel frame-shear wall	22	32.84	13	15.48
Simple Steel frame	7	10.45	14	16.67
Braced steel frame	20	29.85	27	32.14
Total Frames	**67**		**84**	

Table 4: Properties of Steel Frames

Span of Frames	5 m	Height of Storey	3.2 m
Dead load of stories	550 kg/m^2	Dead load of roof	600 kg/m^2
Live load of stories	200 kg/m^2	Live load of roof	150 kg/m^2
Strength of concrete	250 kg/cm^2	Strength of steel	2400 kg/cm^2
Blast Load	CFX	Earthquake load	ASCE

Analysis and design have been done by ANSYS and MATLAB and structures are in elastic limit. For assessment of structural behaviour in nonlinear limit and calculation input and hysteretic energies and evaluation of vulnerability of structures, the latest version of IDARC nonlinear analysis program and MATLAB software was used[20]. Steel frame buildings, steel buildings and masonry infill panels can be modelled using this program. By considering log-normal distribution, probability of exceedance with respect to a damage state at various PGA level can be obtained and fragility curves will be constructed. Figure 2 to 4 are shown fragility curves of two regions with stochastic approach.

Fuzzy Expert for Fragility Analysis

A fuzzy expert system is an expert knowledge-based system that contains the fuzzy algorithm in a simple rule base. In this system, the knowledge, encoded in the rule base, is originated from human experience and intuition and the rules represent the relationships between the inputs and outputs of a system[30]. A fuzzy expert system is comprised of four constituents: fuzzifier, knowledge base, inference engine, and deffuzifier (Figure 3):

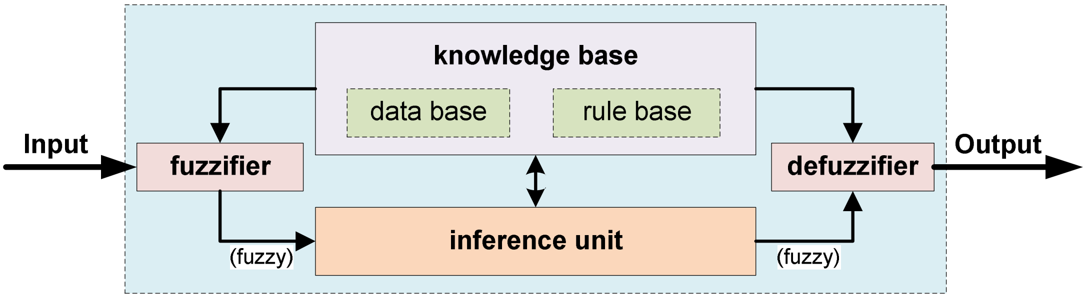

Figure 1: Fuzzy Expert Systems Perform Fuzzy Reasoning

“The Fuzzifier performs fuzzification, which is ‘to convert real numbers of input into fuzzy sets.”The knowledge base includes a database and a rule base. Database consists of ‘membership functions of the fuzzy sets,’ whereas the rule base includes ‘a set of linguistic statements in the form of IF-THEN rules with antecedents and consequents, respectively, connected by AND operator (other operators such as OR, and NOT may be used).’The inference engine that forms the core of a fuzzy expert system utilizes IF-THEN rules included in the rule base to deduce the output through fuzzy or approximate reasoning. The approximate reasoning procedure is to develop conclusion from a set of IF-THEN rules along with some specified conditions.The defuzzifier defuzzifies the fuzzy output elicited by the inference engine through converting it to a real number domain. The centre of area (COA) is the most popular defuzzification method[30] which illustrate fron figure 2 to 6.

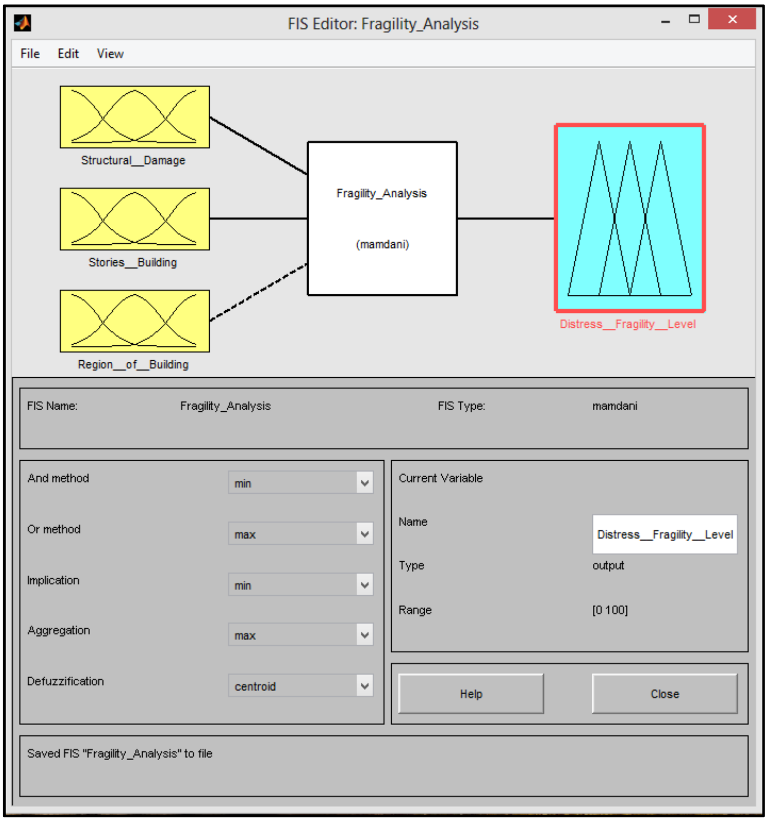

Figure 2: Membership Functions

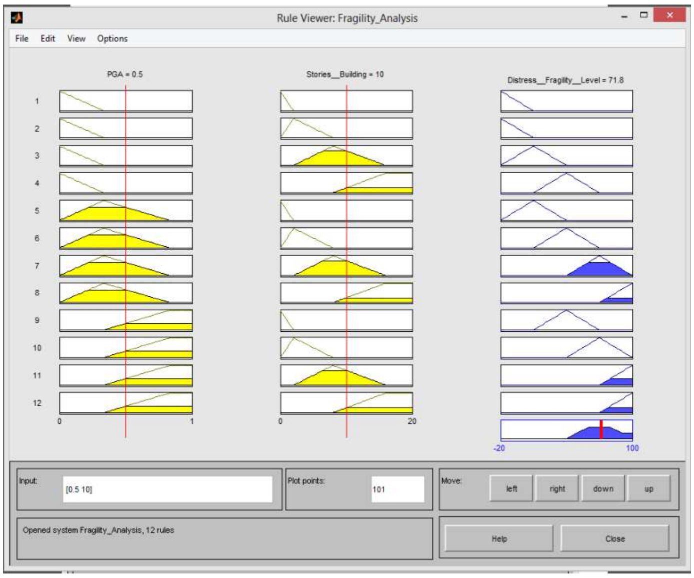

Figure 3: Fuzzy Computations

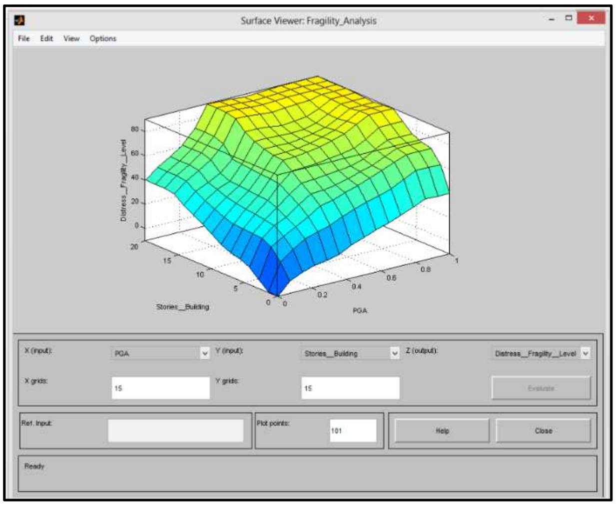

Figure 4: Illustration of the Developed Fuzzy Inference System

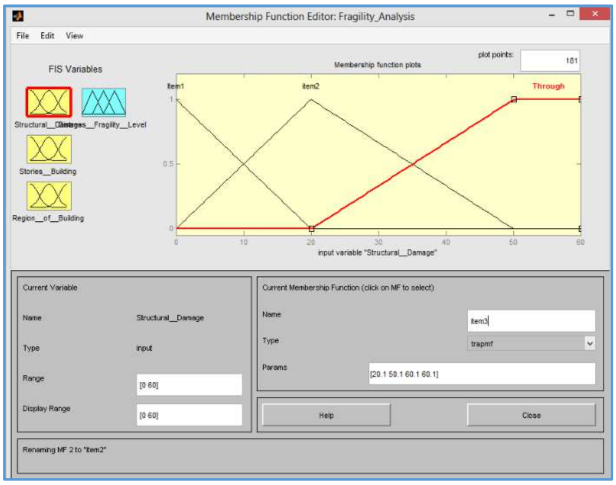

Figure 5: Fuzzy Membership Functions

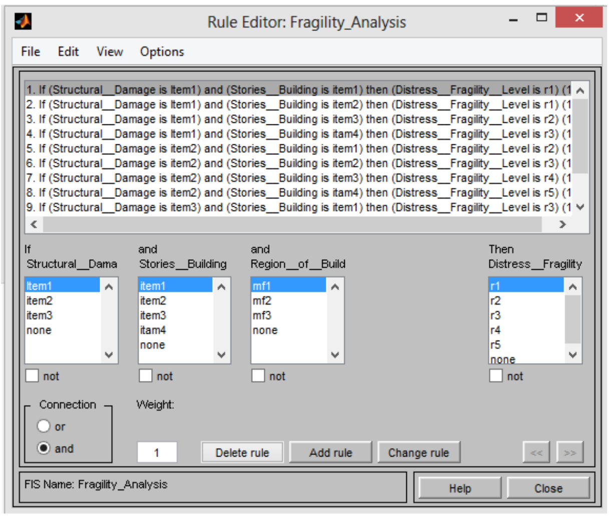

Figure 6: Fuzzy Rules Functions

CONCLUSIONS

Fragility curves can anticipate the damage to structures in future probable earthquakes and show effect of parameters on seismic behavior.As seen in Figures of each region, it is observed that generally the structural damage increases with an increase in the number of stories, from 4 to 12, and the difference becomes more significant in severe states of damage. For the most probable earthquakes, which are the ones with moderate intensity (0.2 g < PGA < 0_5 g, following results could be recognized:

- In region 1 nonstructural and slight damage definitely occur, especially in 4 and 12 stories buildings. Moderate damage is probable and this damage state is more possible in more than 1 g level. The probability of occurring severe damage is possible more 0.3g and increase from 4 to 12 stories building and the probability of exceedance in 1 .5 g is about 60% for 4 and 8 stories and 70% for 12 stories. Maximum probability of collapse in 1 .5g is about 45% for 12 stories.
- In region 2 nonstructural and slight damage are completely possible, especially in 8 and 12 stories buildings. Moderate damage is the most probable for 12 stories building and more than 70% in 0.5g. The probability of occurring severe damage is possible more 0-3g and the probability of exceedance in 1.5 g is about 65% for 4 stories, 75% for 8 and 12 stories. Maximum probability of collapse in 1.5g is about 60% for 12 stories.

By comparison between fragility curves it's found that the vulnerability of moment steel frame is more than moment steel frame with shear wall frame and the retrofitting on these frames can be considered in region 2. Since the soil type in region 1 is softer than region 2, Steel frame frame in region 1 is more important than region 2. To verify this matter fragility curves of Steel frame frame in region 1 can be obtained by considering soil-structures interaction. Thus all frame without any lateral load bearing system and tall building should be retrofitted in region 1. However, soil-structure interaction could increase or decrease the seismic demand depending on the type of structure, the input motion characteristics and the dynamic soil characteristics. Further investigations in this way will be needed in order to obtain more general conclusions for diverse structure based on this fuzzy method.

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